UNIVERSITY OF SOUTHERN CALIFORNIA

SCHOOL OF ENGINEERING

UNIVERSITY RESEARCH INITIATIVE

CENTER FOR THE INTEGRATION OF OPTICAL COMPUTING

F49620-87-C-0007

ANNUAL TECHNICAL REPORT

For the Period
October 1, 1987 through September 30, 1988

Presented to:

The Air Force Office of Scientific Research
Building 410
Bolling Air Force Base, DC 20332

Presented by:

University of Southern California
Department of Electrical Engineering
Los Angeles, California 90089-0483

Principal Investigators
A. A. Sawchuk and W. H. Steier

USC

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION N/A UNCLASSIFIED	1b RESTRICTIVE MARKINGS N/A
2a. SECURITY CLASSIFICATION AUTHORITY UNCLASSIFIED N/A 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE N/A	3 DISTRIBUTION / AVAILABILITY OF REPORT N/A Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UNIVERSITY OF SOUTHERN CALIFORNIA	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 88-1281

6a. NAME OF PERFORMING ORGANIZATION UNIVERSITY OF SO. CALIFORNIA	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
6c. ADDRESS (City, State, and ZIP Code) UNIVERSITY PARK LOS ANGELES, CA 90089-0483		7b ADDRESS (City, State, and ZIP Code) BOLLING AIR FORCE BASE BUILDING 410 WASHINGTON, DC 20332
8a. NAME OF FUNDING / SPONSORING ORGANIZATION AFOSR	8b OFFICE SYMBOL (If applicable) NE	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-87-C-0007

8c. ADDRESS (City, State, and ZIP Code)
Bldg 410
Bolling AFB, DC 20332

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	3484	A3	

11. TITLE (Include Security Classification)
CENTER FOR THE INTEGRATION OF OPTICAL COMPUTING

12. PERSONAL AUTHOR(S)
A.A. SAWCHUK AND W.H. STEIER

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
ANNUAL TECHNICAL	FROM 10/1/87 TO 9/30/88	10/18/88	27

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
OPTICAL COMPUTING, LASER ARRAYS, DETECTOR ARRAYS, SPATIAL LIGHT MODULATORS, OPTICAL ASSOCIATIVE MEMORIES, and OPTICAL SWITCHING. *(dr)*

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

~~THIS REPORT SUMMARIZES THE WORK PERFORMED BY 10 INVESTIGATIVE GROUPS UNDER THE ABOVE STATED CENTER DURING THE PERIOD 10/1/87 - 9/30/88.~~

THIS REPORT SUMMARIZES THE WORK IN THE CENTER FOR THE INTEGRATION OF OPTICAL COMPUTING. TOPICS REVIEWED INCLUDE DYNAMIC OPTICAL INTERCONNECTION NETWORKS, LOW THRESHOLD LASER ARRAYS, ARRAY RECEIVERS, WAVEGUIDE COUPLED PHOTODIODE ARRAYS, OPTICAL PROCESSORS FOR COMPUTER VISION, SUBTRACTION IN OPTICAL NEURAL NETWORKS, NONLINEAR FABRY-PEROT ARRAYS, ALL OPTICAL ASSOCIATIVE MEMORIES, OPTO-OPTICAL SWITCHING, MBE GROWTH AND CHARACTERIZATION OF MQW STRUCTURES, VOLUME HOLOGRAMS AND SLM'S USING MQW STRUCTURES.

Key words include:

UNCLASSIFIED

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Giles	(202) 767-4931	NE

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNIVERSITY RESEARCH INITIATIVE

CENTER FOR THE INTEGRATION OF OPTICAL COMPUTING

F49620-87-C-0007

ANNUAL TECHNICAL REPORT

For the Period

October 1, 1987 through September 30, 1988

DTIC COPY INSPECTED 6

Presented to:

The Air Force Office of Scientific Research
Building 410
Bolling Air Force Base, DC 20332

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

Presented by:

University of Southern California
Department of Electrical Engineering
Los Angeles, California 90089-0483

Principal Investigators

A. A. Sawchuk and W. H. Steier

CENTER FOR THE INTEGRATION OF OPTICAL COMPUTING
ANNUAL TECHNICAL REPORT

TABLE OF CONTENTS

Director's Overview

We have continued a series of seminars and technical exchange meetings on a regular basis during this past year. These meetings bring together the faculty in the Center to exchange their views on the state-of-the-art in optical computing and provide a forum for faculty to exchange information on the status of the materials, the device, and the systems research which is important to optical computing. These exchanges between the device faculty, the materials faculty and the system faculty have proved very fruitful. Each group has been able to direct their research toward the common goal of achieving a practical integrated optical computer and several new ideas, and new research directions have emerged from these meetings.

The common laboratory space for the Center has been renovated and several of the laboratories are now in use. This common laboratory space brings together the students from the device, the materials, and the systems laboratories, and provides a synergistic atmosphere for their studies and research. At the completion of their degrees, these students will have a broad and diverse base in optical computing and will have a good appreciation of the state of the field. Because of their broad backgrounds, these students should be in great demand in industry.

The research goals of the Center are two-fold: 1) to perform cutting edge research in selected areas of materials, devices, and architectures/algorithms important to the realization of an integrated optical computer, and 2) to conceive and demonstrate one or more group prototype optical computing systems. We have made important progress toward both of these goals.

The progress in the individual research topics is given in the text of this report and in the publications referenced in each research unit. For the first time, we are reporting on research progress on the group demonstration projects that have come out of the group meetings and seminars. These group projects are the results of the Center atmosphere and likely would not have come about without the Center being in existence.

Dynamic Optical Interconnection Networks with Integrated Optoelectronic Transceivers

A. A. Sawchuk and S. R. Forrest

We have developed a design for an optical multistage omega network suitable for interconnecting a 2-D plane of inputs to a 2-D plane of outputs.[1] The network is composed of a sequence of log (2N) stages of perfect shuffle (PS) interconnections combined with N^2, 2 x 2 switching (exchange) modules to form an omega network, which is an example of a full-access network (one in which any input can communicate with any output).[1,2] The shuffle operation is analogous to dividing a deck of cards in half and performing a perfect interleaving of the halves of the deck.

The network requires optical components to perform the shuffling and optoelectronic switching modules, which are dynamic, electrically controlled 4 x 4 crossbar networks that route any of 4 inputs to any of 4 outputs in the sense of a one-to-one permutation (no many-to-one [wire-or] or one-to-many [broadcasting] routings are needed). The output of the 4 x 4 switching modules are optical signals that are routed in 3-D by a set of interconnection optics and free-space propagation to succeeding stages containing switching modules.

There are several possible methods for implementing the fixed interconnection optics.[2,3] Because the interconnections between levels are identical, designs which are easily replicated are desirable. We have developed several experimental implementations of both the 2-D input PS and the folded 1-D input PS network. One method uses a set of four lenses to produce imaging and shuffling, or a single lens with an optical transfer function (OTF) synthesis device (such as a hologram) may be used to produce the same result. In another method for implementing the shuffle, we realize that the 2-D shuffle interconnection basically consists of the deflection of a 2-D array of output beams to another 2-D array, so that the interconnection optics can be thought of as an array of microprisms, one for each output line of the 4 x 4 switching modules. One way to make the 2-D microprism array is to first make a planar shuffle prism which provides the appropriate shuffle deflection in one direction and has no spatial variation in the orthogonal direction. A sandwich of two of these devices oriented orthogonally is placed at the output of the 4 x 4 switching modules to achieve the separable interconnection. A computer-generated hologram (CGH) may be used as the interconnection optics. Although the hologram could achieve the desired 2-D shuffle interconnection, the low diffraction efficiency of thin holograms is a

drawback. A copy of the CGH onto a volume phase material such as dichromated gelatin could provide much higher efficiency, and allow replication for the several levels in the system.

Optoelectronic Repeaters/Switching Modules

Optoelectronic switching modules are required to amplify and route signals in the data paths between the optical shuffle stages. For a planar geometry, the switching modules are 2 input, 2 output devices that either pass signals directly or exchange them. For a volume (3-D) shuffle exchange network, the switching modules are dynamically controllable 4 x 4 crossbar networks.

It is important to note that these optoelectronic switch modules are really generalizations of a one-channel optical receiver/transmitter combination that has many applications in optical interconnections and computing. At present, it is difficult to amplify and regenerate high bandwidth optical signals because the expense, power consumption and large physical size of optical receivers and transmitters. Unfortunately, these existing systems have generally been designed under the constraints of long-haul fiber optics telecommunication systems: very high bandwidth, high sensitivity, high gain, and large allowable power consumption and size. We are beginning the design of integrated receiver/transmitters that are suited to optical interconnection networks. We have developed the following tentative requirements and specifications for integrated optical transceivers suitable for these applications:

1. The system can be viewed as having several distinct circuits and subsystems.

   The detector is a pin photodiode directly driven by the input light. It is followed by an amplifier and driven for the optical source. The output source could be an LED or diode laser. Although the system is for a single channel, appropriate switching circuitry can be included to provide signal routing among an array of channels. Individual detectors can be switched on or off, and the outputs of a single detector can be routed to different detectors for broadcasting. The key to success in this work is to minimize circuit complexity and power dissipation such that they can be implemented in large scale 2D networks. The requirement for low power dissipation will inevitably lead to reduced sensitivity and bandwidth per channel. An appropriate materials

system (e.g. InGaAs) and system architecture needs to be employed such that the tradeoffs thus encountered will not eliminate the advantages gained by the high circuit density.

2. Our initial goal is to make each channel operate over a 1-100 MHz bandwidth, with an input sensitivity of 0.1 microwatt to 1.0 microwatt, and output power of 10 microwatt to 100 microwatt. When used in a digital signal environment, the target signal-to-noise ratio of the channel is such that a bit error probability of at least 10^{-12} is possible.

3. The power consumption for a single channel should be less than 1mW. This goal is set with the idea that photovoltaic power form an external source will be used to energize the receiver/transmitter. The photovoltaic cell will be integrated on the same substrate as the receiver/transmitter. Indeed, photovoltaic powering provides power to strategic locations on this circuit without the parasitic, inductive signals usually associated with metallic interconnections.[1] Furthermore, photovoltaic power eliminates the need for difficult physical interconnection to circuits within the 2D arrays.

4. We intend to use III-V materials and processing technology in implementing the design. The reasons for this are the ability of III-V semiconductors to efficiently detect and emit light.

5. The physical size of one single channel unit should be 1 mm x 1 mm. Also, it is desirable to have the input and output wavelengths be the same for ease of cascading a multiple set of devices.

Eventually, other considerations are: crosstalk between multiple channels on the same substrate; power considerations and packing density of an array of devices, and reconfiguration time of any optoelectronic switching or logic elements. All of these considerations will be addressed during the course of this study. However, we strongly believe that the advantages offered by fast optoelectronic switching can be used to great advantage in implementing complex, high density optical interconnects for optical processing, and communication networks.

References

1. H. S. Stone, IEEE Trans. on Computers, **C-120**, 153 (1971).

2. A. A. Sawchuk, Proc. 14th Congress of Int. Comm. for Optics, Quebec, Canada, August 1987. Summary in Proc. 14th Cong. of the ICO, SPIE, **813** (1987).

3. A. W. Lohmann, Optic, **74**, 30 (1986).

Low Threshold Laser Arrays for Optical Computing Applications

P. D. Dapkus

Practical optoelectronic integrated circuits (OEIC's) and monolithic optical computing components require low threshold current laser arrays that are *integrable and simple to fabricate.* Many recent low threshold laser designs depend on technologically complex processes requiring tight dimensional control. We have been investigating the use of two different approaches to the fabrication of lasers by a single growth step using MOCVD. It is our conviction that minimizing the number of processing steps is vital to achieving integrable devices. In our work we have been developing the growth of laser structures on nonplanar substrates and have been exploring the use of impurity induced disordering as means to fabricate lasers with thresholds as low as 1 mA. In this report, we present a low threshold laser design utilizing only a single growth step on an etched substrate to define a narrow active region. Stable, single mode operation with **threshold currents as low as 3.4mA (pulsed, room temperature) and 3.8mA cw** has been achieved in unoptimized devices grown in this manner by MOCVD. These devices, when coated to increase the reflectance of the mirror facets, should operate at threshold currents below 1mA.

MOCVD growth on etched substrate features results in the formation of crystalline facets in the neighborhood of the etched feature. The growth rate on the facets versus the growth rate on the original substrate orientation, usually (001), is a function of growth temperature and the size and orientation of the etched feature. By growing a quantum well on a non-planar surface, the well width, *and consequently the bandgap*, will vary with location on the wafer - mesa or sidewall. This is used in our design to create lateral confinement of the injected carriers. The bending of the grown waveguide structure creates a lateral change in the effective refractive index, promoting transverse optical guiding. We have applied this approach to achieve the *lowest threshold laser grown by MOCVD on a non-planar substrate.*

We name the technique applied in this work Temperature Engineered Growth (TEG). TEG is employed in forming both a narrow active region and a wider contacting region for the low threshold laser. At a low growth temperature of 650°C, the growth rate on the sidewalls is much faster than on the (001) surface, whereas the opposite is true at a growth temperature of 850°C. The width of the mesa after subsequent layers of growth is determined by a simple trigonometric relationship involving the relative growth rate and the angle between the

facet and the (001) surface. In this way, both the width of the mesa and the thickness of individual layers can be controlled by tuning the temperature during epitaxial growth. These phenomena are applied to the TEG of lasers. To accomplish this two parallel channels on close centers are wet etched, forming a mesa a few microns wide. Growth of the lower AlGaAs cladding at 850°C reduces the width of the (001) region above the mesa since the sidewalls grow much slower than the mesa top in this regime. This allows the formation of *sub-micron* active region widths without the need for sub-micron lateral process control. The growth temperature of the quantum well active region is reduced to 750°C. The upper AlGaAs cladding is then grown at lower growth temperatures, significantly widening the (001) region above the mesa to provide a wider region co-planar with the surrounding growth for efficient heat sinking and easy processing for contact stripe definition. A zinc diffusion through a plasma etched opening in a silicon nitride mask provides a conductive channel through the n-AlGaAs current blocking layer.

Pulsed threshold currents (450ns pulses at 10kpps) as low as 3.4mA were obtained with an external differential quantum efficiency (η_{ext}) of about 25% per facet. The same p-side up probe testing of the bars revealed cw threshold currents as low as 3.8mA. A previous wafer, grown entirely at 750°C with an active region width of 1.5μm, had a cw threshold current of 7mA (6mA pulsed) and $\eta_{ext} = 33\%$ per facet. The lower η_{ext} in the present device is probably due to higher optical loss, since the top cladding thickness was less than desired, owing to the higher consumption of material on the sidewall at the lower growth temperature. Near field images of the output facet below and above threshold show a circular spot approximately 1μm in diameter indicating stable, single transverse mode operation due to the lateral guiding provided by the bending of the grown layers.

In conclusion, we have demonstrated low threshold quantum well lasers fabricated *by a new single-step growth technique: Temperature Engineered Growth.* Active regions as narrow as 0.5μm were created with as-grown optical and electronic confinement, using the temperature and structure dependence of MOCVD growth on non-planar substrates. CW threshold currents of 3.8mA have been achieved at room temperature for uncoated devices. Further reduction of threshold current is expected with design optimization. TEG is an attractive technology for arrays and closely packed individually addressable lasers for OEIC and optical computing applications.

Array Receivers for Optical Interconnections

S. R. Forrest

A key to realizing high density arrays of optoelectronic components for use in optical interconnection networks is to devise means to minimize power dissipation and cross-talk. To this end, we have been successful in fabricating InGaAs p-i-n photodiodes and FETs for integrated receiver circuits. The FETs are a self-aligned structure which we have been developing over the last year. We note, however, that while considerable advances have been made worldwide in integrated receiver technology, the results have not been directed to optical interconnection but rather to satisfy the needs for long haul communication networks. Thus, during the last year we have concentrated on developing very low power receivers and logic circuits for high density interconnects. On the analytical side of the effort, a comprehensive model of InGaAs and InP JFETs has, for the first time, been developed. This model applies the various materials of InGaAs and InP parameters including bandgap, effective mass, peak electron velocity, etc. to calculate the power dissipation and sensitivity of optical receivers using optimally designed transistor structures. We obtain the surprising results that gate widths as small as 20 μm can be used to obtain very low power dissipation, high sensitivity receivers. These gate widths and dissipation values are an order of magnitude less than have typically been explored for use in monolithic OEICs for long haul applications. This result is particularly promising since it indicates a higher density of optoelectronic circuits can be tolerated without a significant loss of performance than has heretofore been anticipated.

Experimentally, we have developed fabrication technologies for both detectors and transistors needed for the array receivers being investigated. In addressing the issue of cross-talk, we have introduced the concept of remote, optoelectronic powering and switching of functional array pixels. This concept relies on the ability to fabricate low power dissipation transceivers which minimize the use of inductive power supply and address interconnects via the use of integrated photovoltaic power cells. Thus, power and addressing capability is supplied to each pixel using 0.82 μm wavelength GaAs lasers, while data is supplied at 1.3 μm using InGaAsP technology. A first demonstration of the limitations and advantages of this scheme was implemented on an optical bench using the wavelength division multiplexed system in Figure 1. This optically-powered optical interconnect is effectively an AND gate consisting of a 0.82 μm gate channel and a 1.3 μm data channel. Results from this demonstration are very encouraging, and

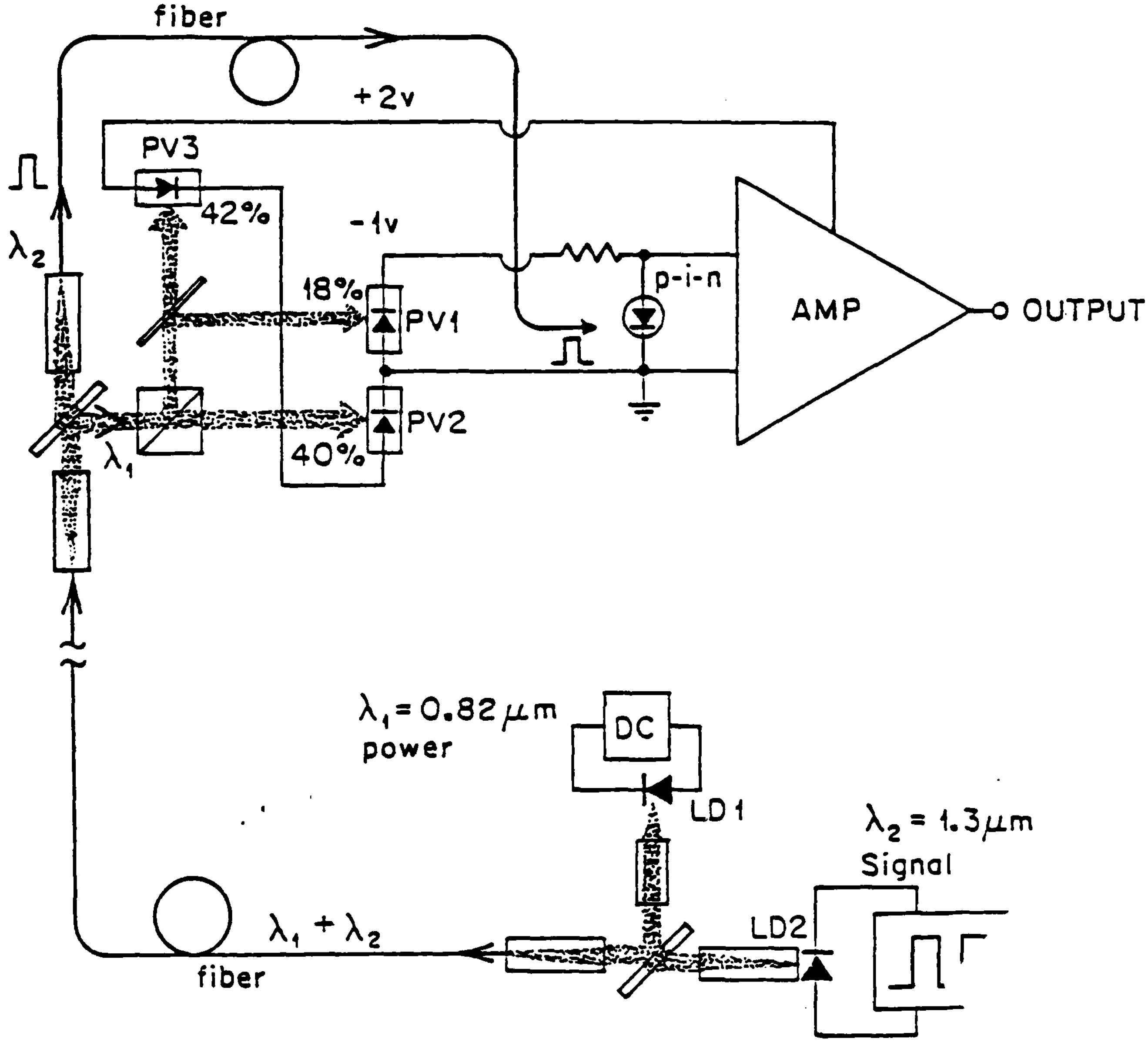
fiber
+2v
PV3
42%
-1v
λ_2
18%
PV1
p-i-n
AMP
OUTPUT
PV2
λ_1
40%
$\lambda_1 = 0.82\mu m$
power
DC
LD1
$\lambda_2 = 1.3\mu m$
Signal
$\lambda_1 + \lambda_2$
LD2
fiber

FIGURE 1

point to its ultimate practicality for use in integrated 2D arrays. Integration of devices appropriate to optically-powered networks will be pursued under separate funding. This work also forms the basis of a group demonstration effort in pursuit of the goals of the URI project.

Optical Interconnects using Waveguide Coupled Photodiode Arrays

S. R. Forrest

During this reporting period, we have successfully demonstrated a high bandwidth organic-on-inorganic semiconductor photodetector for eventual integration into waveguide coupled arrays. The photodetectors consisted of a GaAs or Si substrate on which was deposited 2000 Å of PTCDA followed by approximately 1500 Å of ITO which formed a transparent ohmic contact to the PTCDA. The Si-based detector had an avalanche breakdown voltage (accompanied by photocurrent gain) of 55 V, and a primary reverse current density at 0.9 V_B of approximately 10^{-5} Å/cm.^{2} Also, the external quantum efficiency had a maximum of 85% at a >10V reverse bias, and at a wavelength of 0.8 μm.

The speed of response to 0.82 μm wavelength optical pulses was found to have both a fast and slow component. The slow (~200 ns) response was due to photons absorbed in undepleted regions of the Si substrate, and can be eliminated with proper device design. The fast component (~5 ns) is due to carrier transit across the organic thin film. By reducing the organic film thickness to 50 Å - 100 Å, it is expected that the pulse response of OI photodiodes can be as short as 100 ps, which is adequate for most switching and interconnection applications.

Under separate funding, we have constructed an organic molecular beam epitaxy (or OMBE) system whereby the sample substrate can be cooled to ~80K during organic film deposition. Using this system, we expect in the coming months to succeed in fabricating very smooth surface crystalline organic waveguides, which, when integrated with the fast OI photodetectors, should produce high bandwidth edge-coupled diode arrays.

Optical Processors for Neural Computation of Computer Vision Algorithms

R. Chellappa, B. K. Jenkins and A. A. Sawchuk

The central goals of this research are: 1) to develop efficient algorithms for several Computer Vision problems that can be implemented on artificial neural networks, and 2) to investigate optical implementation of these special purpose neural networks. Over the last 12 months, we have developed and experimented with an 1) algorithm for the extraction of 3-D information from two stereo images, and 2) algorithm for the computation of optical flow. We have presented our work at the International Conference on Acoustics, Speech and Signal Processing at New York in April 1988, and the Second International Conference on Neural Nets at San Diego in July 1988.

The algorithm for matching stereo images uses neural network for matching the estimated first derivatives under the epipolar, photometric and smoothness constraints. Derivatives are estimated using polynomial fits in a local window. Owing to the dense intensity derivatives, a dense array of disparities is generated in only a few iterations. This method does not require surface interpolation, a necessary step in feature-based methods. The algorithm for computation of optical flow matches estimates of principal curvatures obtained from a local window. A neural network is employed to match the estimated principal curvatures under local rigidity and smoothness constraints. Owing to the dense estimates of principal curvatures, a dense field of optical flow estimates is obtained. We have obtained encouraging real experimental results for both the algorithms.

During the third year of the project, we are planning to develop conceptual designs for optical processors implementing the stereo matching and optical flow algorithms.

Subtraction in Optical Neural Networks

B. K. Jenkins

We have developed a model for implementing subtraction in a neuron unit using only incoherent optical devices. It utilizes two optical devices, a linear inverting device and a nonlinear, positive-going soft or hard thresholding device. Functionally, this incoherent optical neuron (ION) model accommodates positive and negative weights, excitatory and inhibitory inputs, non-negative neuron outputs, and can be used in a variety of neural network models. A variant of it can also accommodate bipolar neuron outputs in the case of fully connected networks.

We have simulated the ION model in a version of Grossberg's on-center, off-surround competitive neural network used for nonlinear edge detection and normalization. Many practical effects were simulated, including imperfect device responses, input noise, device noise, drift of the device response, and crosstalk. Spatially correlated and uncorrelated, temporally correlated and uncorrelated, additive and multiplicative noises were simulated. We have found the ION model to be reasonably robust to imperfections and noise, so that a variety of optical devices may be feasible for its implementation.

We are currently performing comprehensive measurements on Hughes liquid crystal light valves (LCLVs) to assess their practicality for use in an experimental demonstration of an optical neural net using IONs. These measurements include input/output response, extinction ratio, input sensitivity, gain, and uniformity over the array.

During the next year of this effort, we will work towards such an experimental implementation of an on-center, off-surround competitive neural network using the ION model. This will incorporate a 2-D array of optical neuron units (IONs) with excitatory as well as inhibitory inputs, and one or more (fixed) holograms for the input and lateral weighted interconnections.

Nonlinear Fabry-Perot Array as a Spatial Light Modulator
Elsa Garmire

We have made a direct measurement of the nonlinear refractive index of AlGaAs/GaAs multiple quantum wells using a modified Twyman-Green interferometer to observe the interference fringes. The measured values of index change agree with those inferred from nonlinear absorption measurements through the Kramers-Kronig relation when the data are normalized to the same carrier density. This experiment is important for providing the validity of inferring nonlinear refractive index from nonlinear absorption data. We have thus proven that scaling to refractive devices from measurements of nonlinear absorption will be correct. The results will be presented at LEOS and have been submitted to JOSA B (H. Sugimoto, M. Kawase, E. Garmire, H. C. Lee and P. D. Dapkus, "Direct Interferometric Measurement of the Nonlinear Refractive Index in AlGaAs/GaAs Multiple Quantum Wells").

We have completed the modeling of Nonlinear Fabry Perots started last year and finished a manuscript which has been accepted for Journal of Quantum Electronics entitled, "Criteria for Optical Bistability in a Lossy Saturating Fabry-Perot." The result of this modeling was that the ratio of the maximum saturated change in refractive index to the linear absorption per unit length must be greater than a third of a wavelength. This puts a great importance on knowing the loss per unit length. We have completed a study relating photo-luminescence to loss in order to determine the below-bandgap loss n these MQWs. This work has been submitted to Applied Physics Letters.

We have observed nonlinear reflection from a quarter-wavelength stack of GaA1As/AlAs layers grown by metalorganic chemical vapor deposition and measured by the pump-probe method. The nonlinearity was primarily due to saturable absorption near the bandedge. Optically-induced reflectivity changes of as much as 0.4 were measured. This work was submitted to Applied Physics Letters (B. G. Kim, E. Garmire, S. G. Hummel, P. D. Dapkus, "A Nonlinear Bragg Reflector based on Saturable Absorption"). This approach has two advantages. First, since it operates in reflection, the opaque substrate does not need to be removed. Second, it may be that loss is not as significant in the multilayer stack as in a Fabry-Perot. Theoretical work is now underway to decide if this is an advantage of the multilayer stack and if it will be more effective than the Nonlinear Fabry-Perot.

We are currently investigating whether optical nonlinearities based on carrier transport can be used to provide nonlinear spatial light modulators. Preliminary work demonstrated very sensitive nonlinearities in both MQW hetero-nipi structures and in hetero-Schokky barriers (A. Kost, E. Garmire, A. Danner and P. D. Dapkus, Appl. Phys. Lett. **52**, 637 (1988), "Large Optical Nonlinearities in GaAs/AlGaAs Hetero-nipi Structure," and N. M. Jokerst and E. Garmire, Appl. Phys. Lett. **53**, 897 (1988), "Nonlinear Optical Absorption in Semiconductor Epitaxial Depletion Regions").

All-Optical Associative Memories
J. Feinberg

We have completed our work on a transient detection microscope, a device which preferentially displays the moving objects in a microscopic scene. This device was featured as the cover article of the March 31, 1988, issue of Nature. A patent disclosure has been filed with the University. We have also made a 5-minute videotape of the device in action. Possible applications of this device include identifying living organisms against a background of inanimate objects, directly observing transmission of an electrical impulse down the axon of a live nerve cell, and detecting any small changes in the synapses of nerve cells during direct electrical stimulation of the nerve.

In collaboration with Prof. Dana Anderson at the University of Colorado in Boulder, Colorado, we have constructed a robot arm that uses an optical fiber and a holographic memory to encode the positions of the arm. This device can remember 128 different and arbitrary positions of a robot arm. Once a sequence of positions is learned (say, picking up an object and twisting it around), a feed-back system can (in principle) be used to step the robot arm through the sequence again. A photorefractive crystal is used to store the various positions of the arm, which are encoded by the speckle pattern from a multimode fiber that is attached to the arm. This device will be described at the upcoming annual meeting of the Optical Society of America next month in Santa Clara, California.

We are continuing our investigation of "double phase conjugators." These devices require two optical beams to produce the phase-conjugate replica of each of the beams. The two beams need not be coherent with each other. A number of geometries have been discovered using photorefractive crystals which permit these double phase conjugators to have large efficiencies, so that 50% of each beam is recovered in the phase-conjugate beam. Depending on the geometry of the crystal and the relative strength of its Pockels coefficients, the devices will require anywhere from 1 to 3 internal reflections inside the crystal to complete their path. The system automatically choses the path that has the most gain. We plan to investigate the precise location and orientation of the self-forming holo-graphic gratings in crystals of barium titanate and strontium/barium niobate. The technique used to locate the gratings is to illuminate the crystals from above with a strong erasing beam, which is scanned across the crystal. When the erasing beam

illuminates a region of the crystal containing a grating, the phase-conjugate efficiency drops. By scanning the beam and measuring the decrement in the phase-conjugate signal, the location of all of the gratings can be mapped out.

Opto-Optical Switching
W. H. Steier

The goal of this work is the invention and study of materials and device structures which can be used to control or switch an information carrying optical beam by a control optical beam. The control beam can be on the same path as the signal beam (tag controlled switching) or can be on a path which is distinct from the signal beam. For tag-controlled switching, the signal beam is differentiated from the control beam by polarization, time slot, or wavelength. Arrays of these beam control devices are critical elements in many optical computing systems particularly in the neural net approaches.

Significant progress has been made in this past year in the development and understanding of a class of nonlinear materials denoted as charge transport assisted effects. For optical switching and optical thresholding devices, a χ_3 type of optical nonlinearity is required in which the index of refraction is changed by the intensity of the optical beam. Unfortunately, a nonlinear effect of this type which is large enough to be of interest for devices is either too slow or is extremely wavelength selective. An alternative to the χ_3 materials is a χ_2 material coupled with a charge transport assisted effect. In this case the optical intensity creates photo charge which diffuses or drifts under the influence of an electric field to create a space charge field within the material. This space charge field changes the index through the electrooptic effect or through a band edge shift (Stark effect). Notable examples of this type of effect are the photorefractive effect and the SEED type devices. The transport assisted effects are in general relatively large with response times of microseconds or less.

We have been studying this effect in CdTe because of its relatively large figure of merit. The figure of merit is defined as n^3r/e where n is the index of refraction, r is the electrooptic coefficient, and e is the relative dielectric constant. This figure of merit is a measure of the change in the index of refraction per photon absorbed. For CdTe this figure of merit is 16 pm/V as compared to that for $BaTiO_3$ of 4.9 pm/V.

We have observed optical switching, optical self switching and optical limiting or thresholding in CdTe:In which has been reported in the literature (see Publications). The signal wavelength can be from 0.9μm to 10μm and the control wavelength can be from 0.9μm to 1.3μm. Switching speeds of 1.0μsec at a control

beam intensity of 10 W/cm^2 are possible. The minimum control beam intensity for switching is 1.0 $milliwatts/cm.^2$

We have also observed what we believe are moving domains of electric charge and high electric field which are initiated by the control beam and move through the material at velocities on the order of 10^4 mm/sec. Moving domains have been observed in high resistivity semiconductors with deep traps and have been attributed to the electron capture coefficient of the traps increasing with electric field. These moving domains cause optical switching and beam deflection and have a great deal of potential for device applications.

In order to understand the dynamics of the charge movement, we have measured the electric field distributions inside the CdTe by probing with a 1.5μm laser and measuring the electrooptic birefringence. The measuring setup consists of a video CCD camera to observe the transmitted light patterns, a video monitor, and frame grabber electronics for isolating a video frame. The single frame data is then fed to a PC for analysis. Measurements of the field patterns have been taken as a function of the applied electric field and the intensity and the wavelength of the control beam. Although not as yet completely understood, these measurements provide a good picture of the time evolution of the charge and voltage patterns inside the semiconductor.

We have observed that the optimum control wavelength is 0.87 to 0.90μm. This wavelength is a compromise between the penetration depth of the beam and the amount of photo charge created. When the CdTe is illuminated by a control beam in this wavelength range, the electric field rapidly moves to a small region just below the negative electrode. The electric field drops to a very low value throughout most of the sample and jumps to a relatively high value just under the negative electrode. We are now measuring the speed and time evolution of this voltage pattern.

In these measurements the control beam is perpendicular to the 1.5μm probe beam and to the applied electric field. For combining these switches into arrays it will be more practical to apply the control beams in the same direction as the applied field. We believe the charge movements and the resultant electric field patterns will be the same in this case. Transparent electrodes will be used to determine if this is true and if arrays can be fabricated in this geometry.

III-V Multiple Quantum Well and Volume Holographic Spatial Light Modulators: MBE Growth and Characterization

A. Madhukar

This past year, we undertook molecular beam epitaxial growth and optical studies of coupled double quantum well (CDQW) structures suited for spatial light modulator (SLM) applications. The underlying physical process being exploited is different from the usual quantum confined stark effect in uncoupled wells in that we are relying on the shift in oscillator strength from selection rule allowed to disallowed transitions in a CDQW under an applied electric field. Photoreflectance, photoluminescence (PL) and PL excitation spectroscopies have revealed the presence of the expected phenomenon, and we are now in the process of optimizing the structural and growth parameters to achieve meaningful contrast ratio between voltage on and off conditions.

As an illustrative example, in Figure 1 is shown the PL emission behavior of a GaAs(40ML)/AlGaAs(5ML)/GaAs(40ML) double coupled quantum well structure under no external bias and a forward bias of 1.5V. Due to the built-in field, the latter is close to the flat band condition. Note the transfer of oscillator strength from the higher to the lower energy peak as one moves away from the true flat band condition. The observed shift in peak energy of ~20 meV is consistent with that estimated for the ~20 KV/cm field operative at 1.5V.

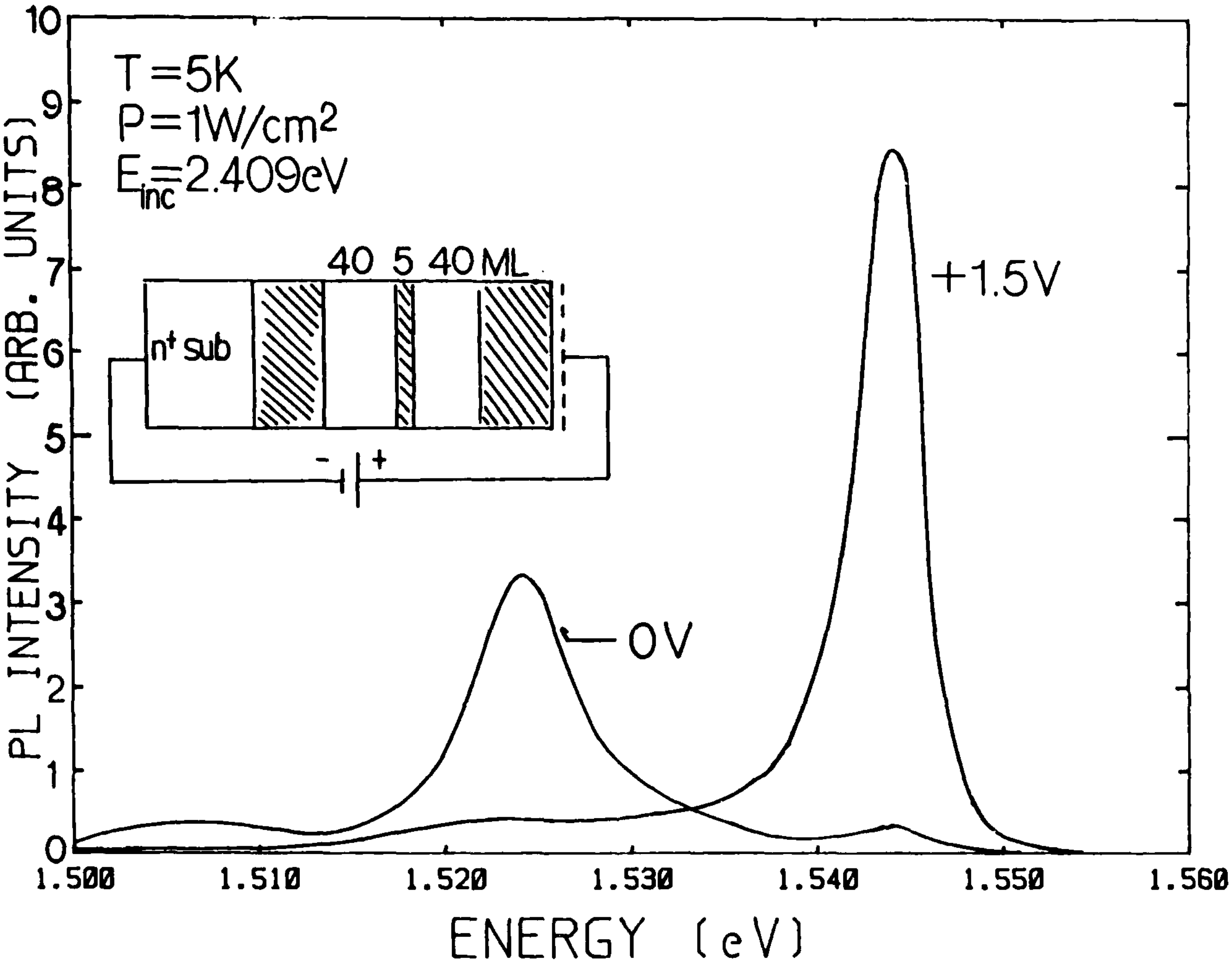
T=5K
P=1W/cm2
Einc=2.409eV
40 5 40 ML
n+ sub
- +
+1.5V
0V
PL INTENSITY (ARB. UNITS)
ENERGY (eV)
0
1
2
3
4
5
6
7
8
9
10
1.500
1.510
1.520
1.530
1.540
1.550
1.560

FIGURE 1

Volume Holographic Optical Elements and Spatial Light Modulators Using Multiple Quantum Well Structures

A. R. Tanguay, Jr. and R. V. Johnson

A number of critical device needs have been identified that are necessary for the integration of optical computing systems. These include spatial light modulators (optically, electronically, and scroll addressed), dynamically reprogrammable volume holographic optical elements for complex interconnection patterns, and variable threshold arrays. The state of the art in these crucial component technologies has heretofore been based on a wide range of disparate device concepts, in each case dependent on materials systems that are at once relatively undeveloped, difficult to manufacture, inflexible in design, and unleveraged with respect to parallel component developments.

In this project, we are investigating novel device concepts for the development of these critical components based primarily on multiple quantum well structures in the III-V compound semiconductor system. The advantages of such components are numerous, including the advanced state of development of III-V materials characterization; the flexibility in device design proffered by microfabrication technologies; and the extensive scientific and technological leverage provided by rapidly advancing parallel developments in array fabrication, electronic component development, source and detector availability, and the discovery and investigation of large electric field induced modulation effects (e.g. the Quantum Confined Stark Effect).

In the spatial light modulator category, we are examining three potential methods of achieving area arrays of modulatable elements with large induced modulation effects. These include photorefractive incoherent-to-coherent optical conversion (PICOC), in which a grating written coherently within a bulk or multiple quantum well (MQW) structure is selectively erased by an information bearing image[1] utilization of the Quantum Confined Stark Effect, which can be employed to produce very large amplitude and/or phase perturbations as a function of an optically or electronically addressed applied field; and the use of modulated doping superlattices to provide large changes in the carrier density with increasing applied field, with resultant optical modulation effects.

To these ends, we have recently demonstrated spatial light modulation utilizing the PICOC geometry in undoped high resistivity GaAs single crystals, in collaboration with Dr. Li-Jen Cheng of the Jet Propulsion Laboratory. Work is

underway to optimize the experimental geometry and device operational mode, in order to assess the maximum resolution, sensitivity, and response time achievable. In collaboration with Prof. Anupam Madhukar's research group at USC, we are investigating both coupled quantum well and nonuniform quantum well structures that may yield enhanced modulation effects as well as optimized figures of merit for spatial light modulation.[2] Preliminary device structures fabricated by molecular beam epitaxy (MBE) techniques have demonstrated unusually large modulation effects. Finally, we are also pursuing the utilization of heterojunction nipi structures in compound semiconductor spatial light modulators, in collaboration with Dr. Joe Maserjian and Dr. Frank Grunthaner at the Jet Propulsion Laboratory. The central thrust here is to examine structures in which large spatial separations between photo-induced electron and hole populations can be induced and maintained, in order to dramatically increase the minority carrier lifetime and thereby enhance the device photosensitivity.

During the most recent research period, we have acquired hardware and software tools for VLSI design, and plan to use the MOSIS service of the Information Sciences Institute at USC to explore possible monolithic and hybrid integrated implementations of optical and electronic spatial light modulator functions, initially on silicon substrates, but eventually on gallium arsenide substrates as that option becomes available to us. Our interests include optically, electronically, and scroll-addressed spatial light modulators, as well as "smart" devices with local circuitry and nearest neighbor interconnections. Our immediate goals to this end are to integrate optical detection and analog drive circuitry in silicon to assess issues such as the tradeoff between functionality and packing density.

In the dynamically programmable volume holographic optical element category, we are investigating a novel structure invented at USC that employs active layers separated by buffer layers to achieve Bragg limited diffraction performance in structures with extremely thin active layers. These Stratified Volume Holographic Optical Elements (SVHOEs)[3,4] have the potential to exhibit high speed, excellent diffraction efficiency, and structural fault tolerance due to the nature of the holographic storage process. In addition, such SVHOE structures exhibit unique and useful optical properties, such as the generation of equal diffraction efficiency, equally spaced interconnections, and the capability for optical and/or voltage programmability of the actual diffraction process. These properties are of great current interest in optical processing and computing, as they allow foı potential programmable interconnection of cellular logic arrays and high density interconnections with partially replicated structures.

We have performed extensive numerical analyses of SVHOE structures to better understand the design issues and performance constraints of this class of devices. One result of this study is the observation that the storage capacity scales approximately as the square of the number of active layers in the device. Another surprising result is that particular spatial frequencies exist for which the device exhibits a significantly reduced response, suggesting possible applications as a programmable notch filter.[5] Experiments have been performed in passive media (photoresist and photographic film) to test key features of the numerical model, and excellent agreement has been observed.

An interesting class of active media for SVHOE implementation is that of the subset of nonlinear organic polymers that exhibit a significant photorefractive effect. We have tested several samples of such polymers in collaboration with Celanese Corporation, and have observed active SVHOE modulation in one such sample that involves a liquid crystal copolymer phase transformation. Characterization of SVHOE structures fabricated in such media is continuing.

Another especially interesting candidate medium for the active recording layer in SVHOE devices is that of III-V compound semiconductor multiple quantum well structures. Multiple quantum well structures have been shown to exhibit very high optical modulation effects within extremely thin layers. As discussed earlier, we are in process of examining a heterojunction nipi structure fabricated at JPL for use in active SVHOE devices, as well as a GaAs/AlGaAs multiple quantum well structure grown on a transparent GaP substrate by MOCVD techniques within the research group of Prof. Dan Dapkus at USC. A number of issues must be resolved in such MQW implementations, including maximizing the optical phase modulation while minimizing background absorption, and understanding and optimizing mechanisms for transverse as opposed to longitudinal spatial modulation of the optical characteristics of the MQW layers.

In parallel with these efforts to develop advanced optical processing and computing components, we have undertaken an intensive study of the fundamental physical limitations that impact achievable device and system performance. In the area of spatial light modulation, such studies include the analysis of quantum fluctuation effects in incoherent-to-coherent optical conversion,[2] the quantification of the resolution/sensitivity/dynamic range/frame rate tradeoff[6], and the assessment of optical, clocked, and scrolled address mechanisms. In the area of volume holographic optical elements, we have addressed the relative insensitivity of photorefractive volume holographic optical elements by analysis of the differential quantum efficiency for grating formation,[6,7] limits to the saturation

diffraction efficiency, bounds on the total information capacity per unit volume, and the effects of volume hologram segmentation into active and passive layers (as in the SVHOE concept described above). Analyses of related systems considerations have included an assessment of the energy bounds for various computational models,[6] an analysis of computational complexity per decision plane,[6] and an energy-based comparison of analog and digital representation schemes.[2,6]

In the area of optical information processing and computing systems, we have undertaken a collaborative effort with Prof. Keith Jenkins of USC to examine the role of highly multiplexed holographic optical interconnections in potential implementations of neural networks. In this investigation, the emphasis is being placed on dynamic reprogrammability issues as they relate to the capacity of a neural network for learning, forgetting, and selective unlearning. A central issue is the nature of the information recording mechanism, and the optimum operational mode for providing the requisite system functionality.

References

1. J. Yu, D. Psaltis, A. Marrakchi, R. V. Johnson, and A. R. Tanguay, Jr., "Photorefractive *Incoherent-to-Coherent Optical Conversion*", *in* Photorefractive Materials and Applications, J. P. Huignard and P. Gunter, Eds., Springer-Verlag, New York, (1988); (in press).

2. C. Kyriakakis, P. Asthana, R. V. Johnson, and A. R. Tanguay, Jr., "Spatial Light Modulators: Fundamental and Technological Issues", Proc. Optical Society of America Topical Meeting on Spatial Light Modulators, Lake Tahoe, Nevada, (1988); (Invited Paper).

3. R. V. Johnson and A. R. Tanguay, Jr., "Stratified Volume Holographic Optical Elements", Opt. Lett., 13(3), 189-191, (1988).

4. R. V. Johnson and A. R. Tanguay, Jr., "Stratified Volume Holographic Optical Elements", Optics News, Special Issue on Optics in '88, Dec., (1988); (Invited Paper).

5. A. R. Tanguay, Jr., "Electro-Optical Information Processing and Computing Components", Proc. Conference on Lasers and Electro-Optics, Anaheim, California, (1988); (Invited Paper).

6. A. R. Tanguay, Jr., "Physical and Technological Limitations of Optical Information Processing and Computing", MRS Bull., XIII(8), 36-41, (1988).

7. R. V. Johnson and A. R. Tanguay, Jr., "Fundamental Physical Limitations of the Photorefractive Grating Recording Sensitivity", in Optical Processing and Computing, H. Arsenault and T. Szoplik, Eds., Academic Press, New York, (1988); (in press).

Publications

1. B. K. Jenkins and C. H. Wang, "Model for an Incoherent Optical Neuron that Subtracts", Optic Letters, to appear, Oct. 1988.

2. C. H. Wang and B. K. Jenkins, "Implementation Considerations of a Subtracting Incoherent Optical Neuron", Proc. IEEE International Conference on Neural Networks, San Diego, July 1988.

3. Y. T. Zhou, R. Chellappa, A. Vaid, and B. K. Jenkins, "Image Restoration Using a Neural Network", IEEE Trans. Acoust. Speech and Signal Processing, Vol. ASSP-36, pp. 1141-1151, July 1988.

4. Y. T. Zhou and R. Chellappa, "Computation of Optical Flow Using a Neural Network", Intl. Conf. on Neural Networks, San Diego, July 1988.

5. Y. T. Zhou and R. Chellappa, "Stereo Matching Using a Neural Network", Intl. Conf. on Acoust., Speech and Signal Processing, New York, NY, pp.940-943, April 1988.

6. J. P. Jiang and J. Feinberg, "Dancing Modes and Frequency Shifts in a Phase Conjugator", Optics Letters 12, 266-268, 1987.

7. R. S. Cudney, R. M. Pierce, and J. Feinberg, "The Transient Detection Microscope", Nature 332, 424-426,1988.

8. J. Feinberg, "Dancing Modes", 16mm movie 1987.

9. R. S. Cudney, R. M. Pierce, and J. Feinberg, "Nonlinear Optical Microscope", VHS movie, 1988.

10 F. F. So, S. R. Forrest, H. L. Garvin, and D. J. Jackson, "A Fast Organic-on-Inorganic Semiconductor Photodetector", Int. and Guided Wave Optics Tech. Digest (OSA), Santa Fe, NM. March 1988.

11. F. F. So and S. R. Forrest, "Organic-on-Organic Semiconductor Photodetector", accepted for publication by IEEE Transaction on Electron Devices, 1989.

12. Y. Liu, J. J. Brown, D.C.W. Lo, and S. R. Forrest, "Optically Powered Optical Interconnection Systems", accepted for publication IEEE Photonics Technology Letters, 1, 1989.

13. Y. Liu, J. J. Brown, D.C.W. Lo, and S. R. Forrest, "Optically Powered Interconnects", Optical Fiber Communication Conference, Houston, TX, 1989.

14. D.C.W. Lo and S. R. Forrest, "Optimum Design of InGaAs and InP Junction Field Effect Transistors by Optoelectronic Integrated Circuits", Optical Fiber Communication Conference, Houston, TX, 1989.

15. K. M. Dzurko, E. P. Menu. C. A. Beyler, J. S. Osinski and P. D. Dapkus, "Low Threshold Lasers Grown by MOCVD on Non-Planar Substrates", Post-Deadline Paper PD-10, 11th IEEE International Semiconductor Laser Conference, Boston, MA, 1988. Submitted for Publication to Applied Physics Letters.

16. K. M. Dzurko, E. P. Menu and P. D. Dapkus, "Atmospheric Pressure MOCVD Growth of GaAs and AlGaAs on Structured Substrates", Paper D-11, 15th International Symposium on GaAs and Related Compounds, Atlanta, GA, 1988.

17. K. M. Dzurko, E. P. Menu and P. D. Dapkus, "MOCVD Growth of AlGaAs on Structured Substrates - A New Tool for Device Design", IEEE LEOS '88 Annual Meeting, Santa Clara, CA, 1988.

18. K. M. Dzurko, E. P. Menu, C. A. Beyler, J. S. Osinski, and P. D. Dapkus, "Temperature Engineered Growth of Low Threshold Quantum Well Lasers by Metalorganic Chemical Vapor Deposition", submitted for publication to Applied Physics Letters.

19. A. Kost, M. Kawase, E. Garmire, H. C. Lee, A. Danner, A. Hariz and P. D. Dapkus, "Nonlinear Measurements in Multiple Quantum Wells of GaAs/AlGaAs Fabricated by MOCVD", SPIE 881, 122-130, 1988.

20. H. C. Lee, A. .ost, M. Kawase, A. Hariz, P. D. Dapkus, E. Garmire, "Nonlinear Absorption Properties of AlGaAs/GaAs Multiple Quantum Wells Grown by Metalorganic Chemical Vapor Deposition", IEEE J. Quantum Electronics, August 1988.

21. W. H. Steier, J. Kumar, and M. Ziari, "Infrared Power Limiting and Self Switching in CdTe", Appl. Phys. Lett., September 1988.

22. W. H. Steier, J. Kumar, and M. Ziari, "Opto-Optical Switching in CdTe", presented CLEO, Anaheim, CA, Paper THW3, April 1988.

23. R. V. Johnson and A. R. Tanguay, Jr., "Stratified Volume Holographic Optical Elements", Opt. Lett., 13(3), 189-191, 1988.

24. R. V. Johnson and A. R. Tanguay, Jr., "Stratified Volume, Holographic Optical Elements", Opt. News, Special Issue on Optics in '88 (in press), (invited paper), 1988.

25. R. V. Johnson and A. R. Tanguay, Jr., "Fundamental Physical Limitations of the Photorefractive Grating Recording Sensitivity", in Optical Pocessing and Computing, H. Arsenault and T. Szoplik, Eds., Academic Press, New York (in press), 1988.

26. A. R. Tanguay, Jr. and R. V. Johnson, "Stratified Volume Holographic Optical Elements", 1986 Annual Meeting of the Optical Society of America, Seattle, Washington, 1986.

27. K. Rastani, Z. Karim, R. V. Johnson, and A. R. Tanguay, Jr., "Optical Information Processing Components", Gordon Research Conference on Optical Information Processing and Holography, Santa Barbara, California (invited paper), 1987.

28. A. R. Tanguay, Jr. and R. V. Johnson, "Stratified Volume Holographic Optical Elements", Conference on Lasers and Electro-Optics, Baltimore, Maryland, 1987.

29. A. R. Tanguay, Jr., "Electro-Optical Information Processing and Computing Components", Conference on Lasers and Electro-Optics, Anaheim, California (invited paper), 1988.

30. C. Kyriakakis, P. Asthana, R. V. Johnson, and A. R. Tanguay, Jr. "Spatial Light Modulators: Fundamental and Technological Issues", Optical Society of America Topical Meeting on Spatial Light Modulators, Lake Tahoe, Nevada (invited paper), 1988.

31. G. P. Nordin, R. V. Johnson and A. R. Tanguay, Jr., "Physical Characterization of Stratified Volume Holographic Optical Elements", 1988 Annual Meeting of the Optical Society of America, Santa Clara, California, 1988.

32. P. Asthana and A. R. Tanguay, Jr., "Charge-Screening-Induced Switching in Spatially Multiplexed Sub-Holograms in $Bi_{12}SiO_{20}$", 1988 Annual Meeting of the Optical Society of America, Santa Clara, California, 1988.

33. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "Binary Image Algebra and Digital Optical Cellular Image Processors", Topical Meeting on Optical Computing Technical Digest Series 1987, Vol. 11, Optical Society of America, Washington, D.C., 1987, Paper MB5, pp. 20-23.

34. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "Binary Image Algebra Representations of Optical Cellular Logic and Symbolic Substitution", OSA Annual Meeting, Rochester, NY, October 18-23, 1987.

35. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "Programming a Digital Optical Cellular Image Processor", OSA Annual Meeting, Rochester, NY, October 18-23, 1987.

36. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "Optical Cellular Logic Architectures Based on Binary Image Algebra", Proc. IEEE Computer Society Workshop on Computer Architecture for Pattern Analysis and Machine Intelligence, Seattle, WA, October 1987, pp. 19-26.

37. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "A Cellular Hypercube Architecture for Image Processing", Applications of Digital Image Processing X, Proc. of SPIE - The International Society for Optical Engineering, Vol. 829, San Diego, CA, August 1987.

38. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "Binary Image Algebra and Optical Cellular Logic Processor Design", to appear in Computer Vision, Graphics and Image Processing.

39. A. Armand, A. A. Sawchuk, and T. C. Strand, "Nonlinear Optical Processing with Halftones: Accurate Predictions for Degradation and Compensation", Applied Optics, Vol. 26, No. 6, 1987, pp. 1007-1014.

40. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "An Image Algebra Representation of Parallel Optical Binary Arithmetic", submitted to Applied Optics.

41. K. S. Huang, et al, "Implementation of a Prototype Digital Optical Cellular Image Processor (DOCIP)", presented at ICO/SFO Optical Computing 88, Toulon, France, August 29 - September 2, 1988.

42. K. S. Huang, B. K. Jenkins, and A. A. Sawchuk, "Optical Symbolic Substitution and Pattern Recognition Algorithms Based on Binary Image Algebra", presented at ICO/SFO Optical Computing 88, Toulon, France, August 29 - September 2, 1988.